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Haptic feedback for enhancing realism of walking simulations

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Abstract—In this paper we describe several experiments whose goal is to evaluate the role of plantar vibrotactile feedback in enhancing the realism of walking experiences in multimodal virtual environments. In order to achieve this goal we built an interactive and a non-interactive multimodal feedback system. While during the use of the interactive system subjects physically walked, during the use of the non-interactive system the locomotion was simulated while subjects were sitting on a chair. In both the configurations subjects were exposed to auditory and audio-visual stimuli presented with and without the haptic feedback. Results of the experiments provide a clear preference towards the simulations enhanced with haptic feedback showing that the haptic channel can lead to more realistic experiences in both interactive and non-interactive configurations. The majority of subjects clearly appreciated the added feedback. However, some subjects found the added feedback disturbing and annoying. This might be due on one hand to the limits of the haptic simulation and on the other hand to the different individual desire to be involved in the simulations. Our findings can be applied to the context of physical navigation in multimodal virtual environments as well as to enhance the user experience of watching a movie or playing a video game.

Index Terms—Haptic feedback, realism, virtual environments, physics based models.

1 Introduction

WHILE five years ago the design, development, incorporation in virtual world, and perceptual evaluation of haptic technologies was still in early phase [1], nowadays research on haptic feedback is reaching a more mature state. However, the role of haptic feedback to enhance realism in multimodal virtual environments has not been extensively investigated in the research community. A notable exception is the work presented in [2], where realism is improved by simulating tapping with event-based haptic feedback. In addition, results presented in [3] show that haptic force feedback significantly increases the sense of presence in collaborative distributed virtual environments.

On the other hand the use of senses other than vision and hearing has remained relatively unexplored in movies and video games despite a continuous request from the public and gamers for richer experiences while interacting with such media. Nevertheless, recent research efforts have focused on the design and development of non-interactive haptic interfaces for enhancing movies, providing evidence that haptic feedback can play a relevant role in augmenting the theatre experience beyond the visual and the auditory modalities [4], [5], [6]. In addition, the importance of the haptic feedback in video games was raised by Chang [7] who suggested that haptic technologies will become an integral part of the video games design process.

In the research community haptic feedback in a multimodal context has been mostly connected to the interaction with the vision. Nevertheless, lately the interest in investigating the interaction between touch and audition has grown. The possibility of investigating the interaction between auditory and haptic feedback has been facilitated by the rapid progress of haptic technology, together with the development of efficient and accurate simulation algorithms. However, research on the interaction between touch and audition has focused mainly on hand based interactions [8], [9], [10], while few studies have been conducted on the interaction of these two sensory modalities in the feet. One exception is the work of Giordano and co-workers, who showed that the feet are effective at probing the world with discriminative touch, with and without access to auditory information [11]. In particular their results suggested that the vibrotaction plays a relevant role in the discrimination of floor surfaces.

Recently a small number of foot-haptic interfaces for navigation in virtual environments have been proposed. Typically the haptic feedback is provided during the user's locomotion by means of augmented floors [12] or enhanced shoes [13], [14]. Research has shown that the use of plantar cutaneous vibration feedback is sufficient to elicit a percept of compliance during walking [15]. However, the role of the haptic feedback in enhancing the realism of the walking experience in multimodal virtual environments has

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not been empirically demonstrated.

In this paper, we are interested in investigating subjects' reaction to synthetic auditory and haptic stimuli which simulate the sensation of walking on different ground surfaces both in a non-interactive and interactive configuration. Recently we developed a system which can provide combined auditory and haptic sensations that arise while walking on aggregate and solid surfaces. The system is composed of an audio-haptic synthesis engine [16], and a pair of shoes enhanced with sensors and actuators [13].
In a previous study [17], we presented the results of a preliminary surface recognition experiment. This experiment was conducted under three different conditions: auditory feedback, haptic feedback, and both. Participants were sitting in a chair, passively receiving the stimuli through headphones and the mentioned shoes. By presenting the stimuli to the participants non-interactively, we introduced a high degree of control on the simulation. However, this method of delivery is highly contrived since it eliminates the tight sensorimotor coupling that is natural during walking and foot interactions. It is true for the auditory channel, but even more so for the haptic channel. In spite of these drastically constrained conditions subjects were able to recognize most of the stimuli in the audition only condition, and some of the material properties such as hardness in the haptic only condition. Nevertheless, the combination of auditory and haptic cues did not significantly improve recognition.

A follow up experiment was run in another study [18] allowing subjects to walk in a controlled laboratory, where their steps were tracked and used to drive the simulation. Subjects were asked to recognize the different simulated surfaces they were exposed to with uni-modal (auditory or haptic) and bi-modal (auditory and haptic) cues. Overall, results showed that subjects were able to recognize most of the synthesized surfaces with high accuracy. Results moreover showed that, using the proposed system, the auditory modality dominated the haptic one and that the haptic task was more difficult than the other two. Indeed subjects performed the recognition task better when using auditory feedback versus haptic feedback, and the combination of the two typologies of feedback only in some conditions significantly enhanced recognition.

In both [17] and [18] subjects were also asked to rate the degree of realism of the stimuli. Results of both the studies showed that the combination of auditory and haptic feedback did not always enhance the realism of the simulation compared to the uni-modal one. However, those studies followed a between-subjects experimental design, where each subject was presented with either auditory, or haptic or audio-haptic stimuli. Therefore it was not possible to draw any clear conclusion about the effect of the haptic feedback in enhancing the realism of the simulations based on the auditory feedback alone.
Starting from those results, in the present study we describe an experiment where subjects were asked to compare stimuli involving the haptic feedback with those in which the haptic feedback was not present. The role of the haptic feedback in enhancing realism of a walking experience was investigated both in an interactive and a non-interactive context. In order to achieve this goal we built an interactive feedback system and a non-interactive feedback system. While during the use of the interactive system subjects physically walked, instead during the use of the non-interactive system the locomotion was passively simulated while subjects were sitting on a chair. For this latter purpose two case studies which are frequent in both video games and movies were analyzed: walking and running.

2 The Interactive Feedback System

Recently a multimodal interactive architecture has been developed with the goal of creating audio-haptic-visual simulations of walking-based interactions [19] (see Figure 1). The architecture used during the proposed experiments consisted of a motion capture system (MoCap)(Optitrack by Naturalpoint), a nVisor SX head-mounted display (HMD), with 1280x1024 resolution in each eye and a diagonal FOV of 60 degrees, two soundcards (RME Fireface 800), twelve loudspeakers (Dynaudio BM5A), an Arduino Diecimila board, a pair of Pyle Pro PCA14 mini 2X15 W stereo amplifiers, two haptic shoes and two computers.
This system was placed in an acoustically isolated laboratory consisting of a control room and a larger interaction room (5.45 m large, 5.55 m long and 2.85 m high) where the setup was installed and where the experiments were performed. The control room hosted two desktop computers. The first computer ran the motion capture software and the visual engine, while the second ran the audio-haptic synthesis engine. Users were required to wear both the HMD and a pair of shoes enhanced with sensors and actuators able to provide haptic feedback during the act of walking [13]. Specifically, the shoes were a pair of light-weight sandals (Model Arpenaz-50, Decathlon, Villeneuve d'Ascq, France). This particular model was chosen since it has light, stiff foam soles where it is relatively easy to insert sensors and actuators. Four cavities were made in the sole to accommodate four vibrotactile actuators (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada). These electromagnetic recoil-type actuators have an operational, linear bandwidth of 50–500 Hz and can provide up to 3 G of acceleration when connected to light loads [20]. Two actuators were placed under the heel and the other two under the toe of one foot. They were bonded in place to ensure good transmission of the vibrations

inside the soles. When activated, vibrations propagated far in the foam. In addition, the sole had two force sensitive resistors intended to pick the foot-floor interaction force in order to drive the audio and haptic synthesis. The two sensors were placed in correspondence to the heel and toe respectively in each shoe (see Figure 2).
Markers were placed on top of the HMD to track orientation and position of the head. The tracked coordinates were sent from the first to the second computer which processed them in order to control both the visual and the audio-haptic engine.

Concerning the surround sound system, eight loudspeakers were placed on the ground at the vertices of a regular octagon, while four loudspeakers were placed in correspondence to the vertices of the the rectangular floor at the height of 1.40 m. All the loudspeakers were used for the delivery of the soundscapes, while only the eight on the ground were responsible for the diffusion of the footstep sounds. Such configuration was chosen according to the results of preliminary studies on footstep sounds delivery methods.

Fig. 2. A picture of one pressure sensor and two actuators embedded in the shoe in correspondence to the heel.

2.1 Multimodal interactive feedback

A multimodal synthesis engine able to reproduce visual, auditory and haptic feedback was also developed on the basis of the architecture described above. The auditory feedback was obtained by the combination of a footstep and a soundscape sound synthesis engine implemented in the Max/MSP sound synthesis and multimedia real-time platform[1]. The footstep sounds synthesizer employed was the one proposed in [16], which allows to simulate, both offline and in real-time, footstep sounds on several different materials, both aggregate and solid. Concerning the real-time simulation, various systems for the generation of such input have been developed and tested [16], [21]. In the proposed interactive experiments, the footstep sounds synthesis was driven during the locomotion of the subject wearing the above mentioned shoes. The description of the control algorithms based on the analysis of the values of the pressure sensors coming from the shoes can be found in [13].
As concerns the soundscapes diffusion, the environmental sounds were delivered dynamically using a sound diffusion algorithm based on ambisonics. Specifically, to achieve the dynamism we used the ambisonic tools for Max/MSP[2] which allows the movement of virtual sound sources along trajectories defined on a bidimensional and tridimensional space [22].

Regarding the haptic feedback, it was provided by means of the haptic shoes previously described. The haptic synthesis was driven by the same engine used for the synthesis of footstep sounds, and is able to simulate the haptic sensation of walking on different surfaces, as illustrated in [13]. Such audio-haptic footsteps synthesizer has been extensively tested by means of several audio-haptic experiments and results can be found in [17], [18], [23], [24]. During the interactive set of experiments, the laboratory surface on which participants were trampling on was a carpet. For the purpose of the experiment the audio-haptic synthesis engine was set to simulate three aggregate surfaces: forest floor, snow and sand (see Figure 3). Such simulations are based on the physically informed sonic models (PhiSM) algorithm [25]. This algorithm simulates particle interactions by using a stochastic parameterization thereby avoiding needing to model each of many particles explicitly. Instead, the particles are assigned a probability to create an acoustic waveform. In the case of many particles, the interaction can be represented using a simple Poisson distribution, where the sound probability is constant at each time step, giving rise to an exponential probability weighting time between events. Nevertheless, the audio frequency range, viz. 20 Hz-20 kHz, is far wider than the vibrotactile frequency range, viz. 10 Hz-1.0 kHz. In order to simulate the three materials at haptic level the audio signals were converted into vibrotactile signals by means of spectrum truncation, pitch shifting and amplitude adjustment. The spectrum truncation was the result of the frequency response of both the actuators and the shoes. The amount of shift and amplitude were set to preserve the structural features of the original signals simulating the three materials. Indeed, our goal in the design of the haptic feedback was to accomplish the multimodal congruence between audio and haptic cues, with particular regard to their matching in amplitude envelope and temporal evolution.

Concerning the visual feedback provided by the HMD, three outdoor scenarios were developed using

1. www.cycling74.com

2. www.icst.net/research/projects/ambisonics-tools/

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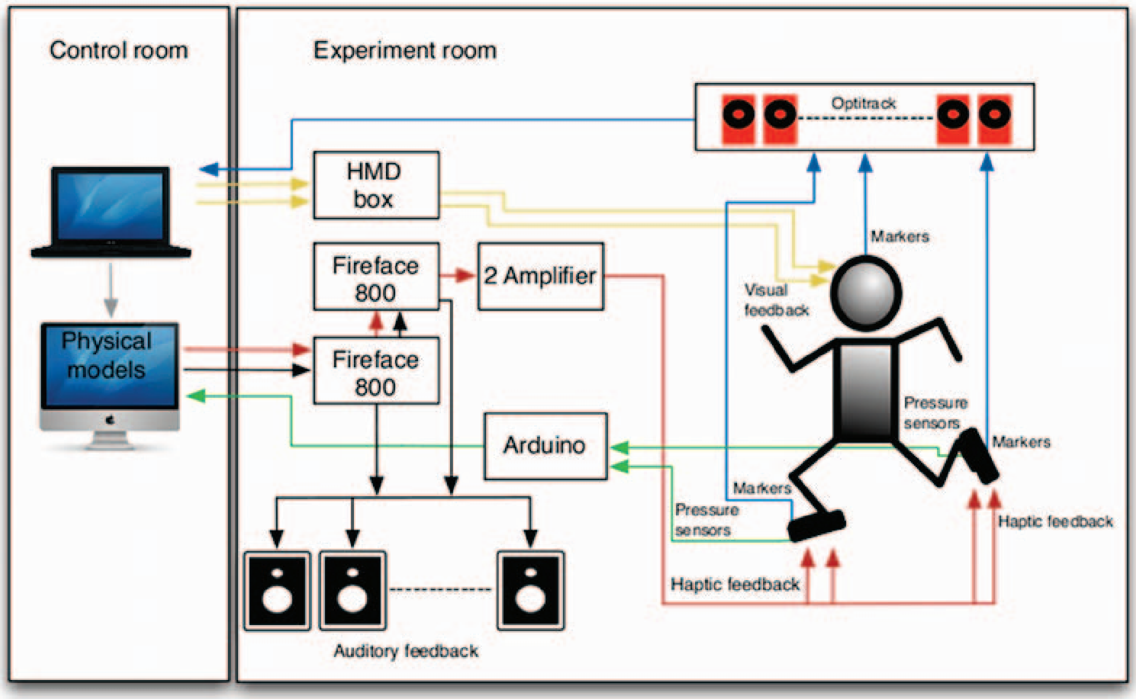

Fig. 1. Schematic representation of the overall architecture developed for the interactive experiments.

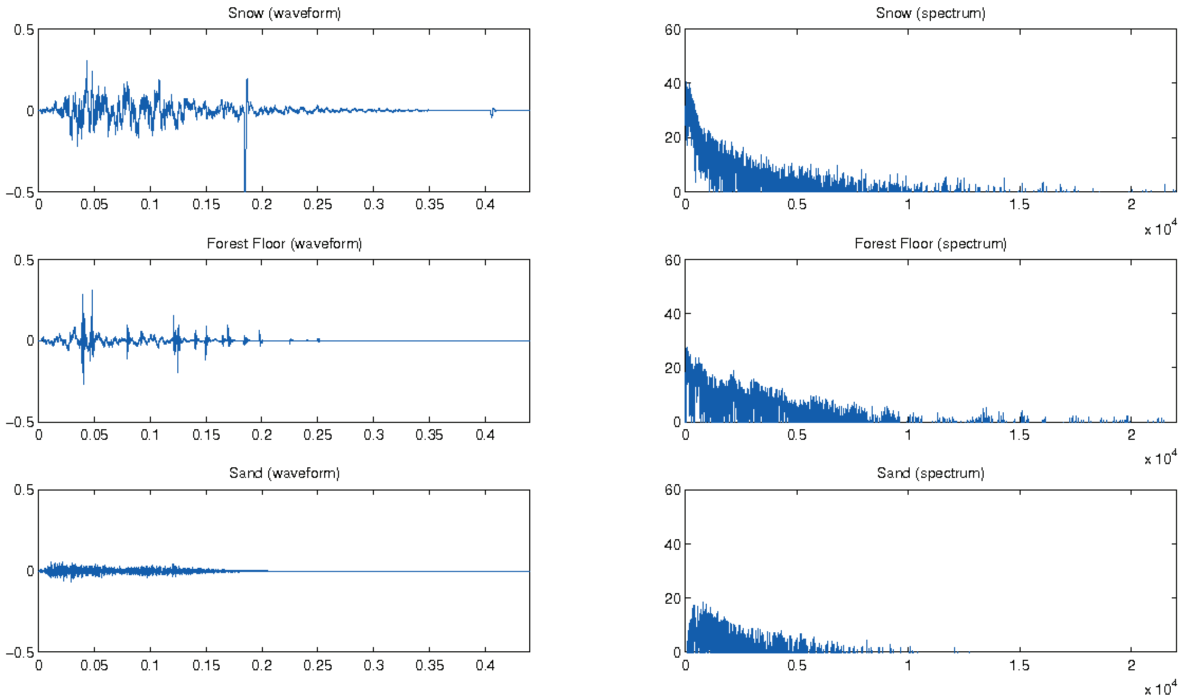

Fig. 3. Typical waveforms (left) and spectra (right) of the three simulated materials. The duration of the waveforms is expressed in milliseconds, the magnitude of the spectra in decibel.

the Unity3D engine[3] in order to render the visual sensation of exploring different landscapes. The goal of such outdoor scenarios was to provide a visual representation of the physically simulated surfaces provided in the audio-haptic engine. In more detail, during the experiments a forest, a snowy landscape and a beach were visually rendered to match the physically simulated forest floor, snow and sand.

The area fully seen by the cameras delimited the zone available for the users to walk. It consisted of a

3. http://unity3d.com/

rectangle 2.50x2.60 m, whose perimeter was indicated in the simulated landscapes by means of a fence.

3 THE NON-INTERACTIVE FEEDBACK SYSTEM

The non-interactive feedback system (see Figure 4) was designed to convey the visual-audio-haptic feedback to the users without any interaction. Users were sitting on a chair passively receiving the multimodal feedback which was provided through the screen of a 15-inch mac book pro laptop, a set of headphones[4], and the haptic shoes previously mentioned.

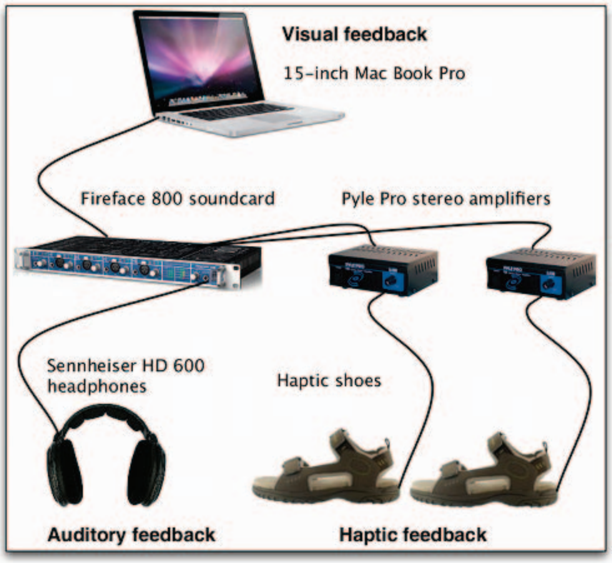

Fig. 4. Schematic representation of the overall architecture developed for the non-interactive experiments.

The visual feedback was developed using the Unity3D game engine and consisted of the same landscapes presented during the interactive experiments with in addition an avatar walking or running over a flat surface. In particular, the experiments included two avatar models to match the participants' gender. The male model was composed by 3754 triangles, while the female model by 4488. Both models featured a skeleton with 39 joints. The walk and run animations were based on motion capture data and have been developed by Mixamo using Stefano Corazza's patented technology [26]. An example of the visual feedback provided in the experiments can be seen in Figure 5. The auditory feedback consisted of audio files containing both soundscapes and footstep sounds. The utilized soundscapes were the same used for the interactive experiments but converted in stereo format. The footstep sounds were created by means of the offline use of the footstep sounds synthesizer utilized during the interactive experiments. This synthesizer is based on physical models which are driven

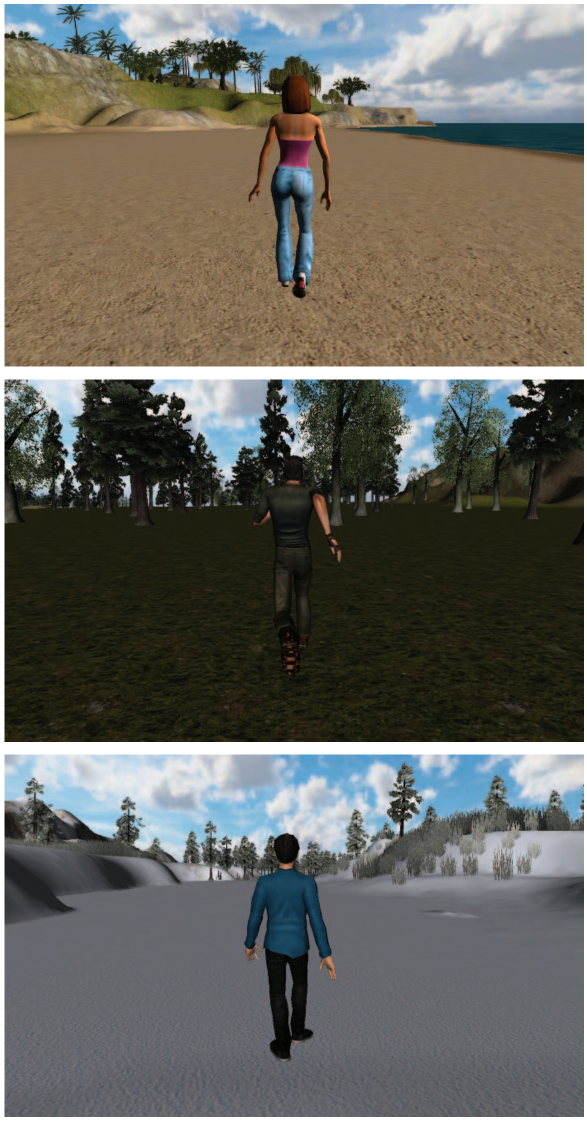

Fig. 5. Three examples of the visual feedback provided in the experiments. From top to bottom: a female walking in a beach, a male running in a forest and a male walking on snow.

by a signal, in the audio domain, expressing the ground reaction force (GRF), i.e., the reaction force supplied by the ground at every step [27]. In our simulations the GRF corresponds to the amplitude envelope extracted from an audio signal containing a footstep sound.

In order to produce the walk or the run over different surface materials, we created different audio files using the recording of real footstep sounds on concrete. Such sounds were chosen among those available in the Hollywood Edge sound effects library.[5] As an example, Figure 6 shows both the waveform and the corresponding extracted GRF of a footstep sound on a concrete floor during the walk and during the run.

4. Sennheiser HD 600, http://www.sennheiser.com

5. http://www.hollywoodedge.com

The time interval between each step was set in order to match the walk and the run of the avatar appearing at visual level, precisely 566.66 and 333.33 milliseconds for the walk and the run respectively. The same audio files were used also during the experiments without the visual feedback. In this regard, in our previous research on audio and haptic simulation of bumps, holes and flat surfaces we found that a surface profile is perceived as flat, both at audio and at haptic level, when the simulated steps are placed at equal temporal distances [24].

For the purpose of the experiments, the engine was configured in order to synthesize footstep sounds on the same surface materials of the interactive experiment (forest floor, snow and sand).

Regarding the haptic feedback, it was generated by means of the same files produced for the auditory feedback, involving the same procedures mentioned in section 2.1 to convert the audio signals into vibrotactile ones. In addition, at haptic level each step was provided alternating the left and the right shoe, coherently with the order of the steps produced visually by the avatar.

4 Interactive feedback experiments

We conducted three between-subjects experiments whose goal was to assess the role of the haptic feedback in enhancing the realism of the footstep sounds interactively generated during the user locomotion. The simulated surface materials were snow, sand and forest floor. Experiment 1 consisted of the presentation audio-haptic footsteps simulations alone, while in experiment 2 and 3 the soundscapes and the soundscapes plus the visual feedback were added respectively. Each experiment was divided in two parts. During the first part participants were exposed to 8 trials lasting each 14 seconds. Each trial consisted of two parts, lasting each 6 seconds, which were divided by 2 seconds of absence of interactive feedback. In three trials the three simulated surfaces were presented in the auditory only condition in the first part and in the audio-haptic condition in the second part (referred as trials A-AH from now on). In three other trials they were presented in the audio-haptic condition in the first part and in the auditory only condition in the second part (referred as trials AH-A from now on). The remaining two trials were used as control condition, and they consisted of the presentation, in both the parts, of the auditory feedback alone and of the audio-haptic feedback respectively. For these two trials the forest floor material was utilized. After the presentation of each trial participants were asked to compare the two parts of the walk by answering the following questions:

- Have you noticed any difference between the first and the second part of the walk?
- If yes, what has changed?
- Which of the two parts do you prefer?
- Why?

At the conclusion of the first part of the experiment participants were told that the difference consisted of the use of the haptic feedback.

During the second part of the experiment participants were exposed to 6 trials, consisting of the same trials presented in the first part without including the control conditions. For each A-AH trials participants were asked to choose one of the following statements:

- The presence of the haptic feedback in the second part of the walk:
  - has increased the realism of the simulation respect to the first part of the walk.
  - has decreased the realism of the simulation respect to the first part of the walk.
  - has not produced any difference in the realism of the simulation respect to the first part of the walk.

Similarly, during the AH-A trials participants were asked to answer the same questions asked for the A-AH trials considering this time the absence of the haptic feedback in the second part of the walk. In case of an answer concerning an increase or a decrease of the realism, participants were asked to evaluate to which extent it occurred, on a 9-points Likert scale (1 = very little, 9 = very much).

In both the parts of the experiment the trials were presented once in randomized order. Participants were instructed to walk also during the two seconds in which the interactive feedback would not have generated.

During experiment 3, one experimenter was placed in the same room where the experiment was performed in order to prevent the participants to fall down because of eventual balance losses due do the visual feedback provided through the HMD.

Our hypotheses were manifold. Concerning the first part of the experiments, we hypothesized that participants would have noticed the presence of the haptic feedback with higher percentages in experiment 1, rather than the other two, with the lowest percentages for the experiment 3. Secondly we hypothesized a clear preference for the audio-haptic condition compared to the auditory one. As regards the second part of the experiments, we expected that the presence of the context (soundscapes in experiment 2 and soundscapes plus visual feedback in experiment 3) would have led to an increase of the evaluated enhancement of the realism of the audio-haptic condition compared to experiment 1.

4.1 Participants

Thirty-six participants were divided in 3 groups (n = 12) to perform the 3 between-subjects experiments. The 3 groups were composed respectively of 9 men and 3 women, aged between 20 and 30 (mean = 24.5,

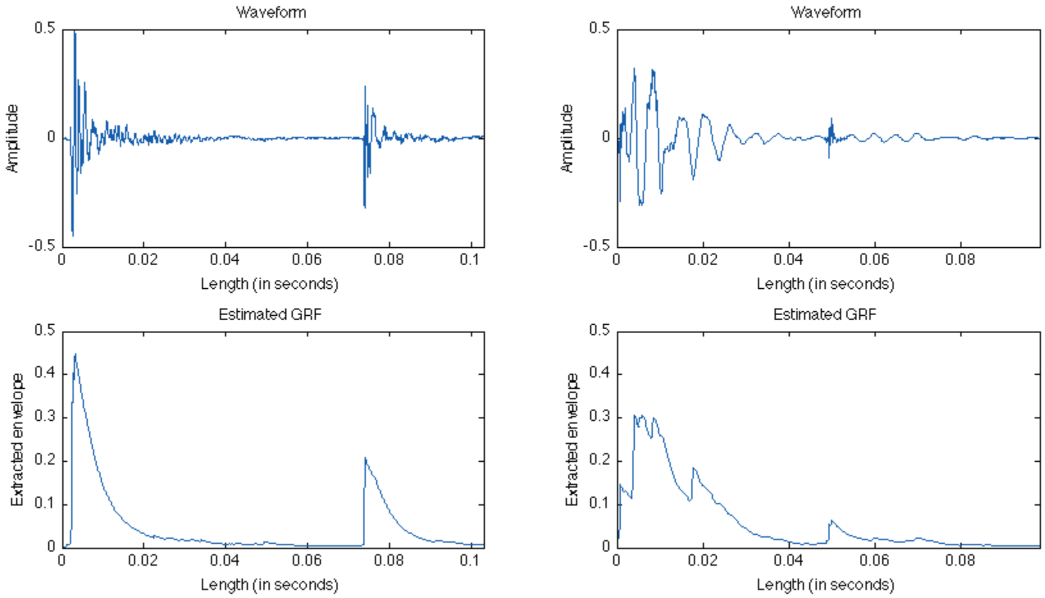

Fig. 6. Waveforms (top) and relative extracted GRF (bottom) of a typical footstep sound on a concrete floor while walking (left) and while running (right). It is possible to notice the different temporal length of the two steps as well as the different times in which the heel and toe strikes occur. In addition in the plots of both the GRFs it is possible to notice the sub-events heel and toe.

standard deviation = 3), 5 men and 7 women, aged between 19 and 25 (mean = 21.5, standard deviation = 1.67), and 11 men and 4 women, aged between 19 and 25 (mean = 21.75, standard deviation = 1.91).
All participants reported normal hearing conditions, normal or corrected-to-normal vision, and no locomotion problems. The size of the used pair of sandals was 43 (EUR). In order for the size of sandals not to affect performance, subjects wore shoes sizes from 41 to 45 (EUR).

4.2 Results

Results of the first part of the interactive feedback experiments are illustrated in Table 1. The first noticeable thing is that on average participants understood quite well that the difference between the two parts of the walk in each trial consisted of the haptic feedback. The significance of this result was confirmed by a binomial test ($p < 0.0001$, $p = 0.0002$, $p = 0.006$, for experiment 1, 2 and 3 respectively). Similarly, they were significantly precise in the evaluations of the control conditions ($p = 0.02$, $p = 0.006$, $p = 0.0002$, for experiment 1, 2 and 3 respectively).
As concerns the preference of the two parts, it was calculated only for the subjects who correctly understood which was the difference. As it is possible to notice, on average participants preferred the audio-haptic condition rather the auditory one, although the percentages of preference were higher for experiment 3 compared to experiment 1 and 2, and for experiment 2 compared to experiment 1. The binomial test revealed that there is a significant preference for the audio-haptic condition only in experiment 2 and 3 ($p = 0.003$ and $p < 0.0001$ respectively).
When asked to motivate their preference, participants who preferred the presence of the haptic feedback answered that their experience interacting with the system seemed to them closer to the real life, more fun, and they even felt it was easier to walk. In addition some participants reported that the realism of the experience was increased by the haptic feedback since they had the impression that sound came directly from their feet, while when the footstep sounds were conveyed alone they had harder time in localizing the sound source under their feet. As a matter of fact, an audible output is generated by the haptic shoes as result of the activation of the actuators. However such sounds have a low amplitude, a low quality and are masked by the footstep sounds produced by loudspeakers.
Conversely, participants who preferred the auditory feedback alone reported that without the haptic feedback the experience was more normal, more comfortable, and less weird. Some participants reported that they had the impression that the vibrations did not fit well with the provided sounds, while others said that they would have expected other types of vibrations.

Table 2 shows the results of the second part of the three interactive feedback experiments. As can be seen, in all the experiments and in all the trials the most part of participants evaluated the haptic feedback as enhancing the realism of the simulations. The binomial test revealed a significant preference for the increment of realism in presence of haptic feedback

($p < 0.0001$, $p = 0.01$, $p < 0.0001$, for experiment 1, 2 and 3 respectively) and for the decrement of realism in its absence ($p = 0.003$, $p = 0.01$, $p < 0.0001$, for experiment 1, 2 and 3 respectively). Concerning the evaluations of the increment of realism in presence of haptic feedback, results show that they are on average higher than 4.5, (i.e. towards the "very much"), therefore this increase is not negligible. The same holds for the evaluations of the decrement of realism in absence of haptic feedback. In addition, comparing the evaluations between the stimuli it is possible to order the surface materials in terms of enhanced realism. Indeed in all experiments snow presented the highest ratings, and sand was rated with ratings higher than forest floor.

From a comparison between the three experiments it emerges that the average values of the increment of realism in trials A-AH, as well as of the decrement of realism in trials AH-A, are lower when the footsteps are simulated alone compared to when they are provided with soundscapes and with soundscapes plus visual feedback. In particular the highest ratings are present for experiment 3. A statistical analysis was performed by means of an ANOVA with repeated measures by considering the three experiments for each of the two dependent variables (increment of realism in presence of haptic feedback, and decrement of realism in absence of haptic feedback). Results revealed that all such differences are not statistically significant.

5 Non-interactive feedback experiments

Three between-subjects experiments were conducted with the goal of assessing the role of the haptic feedback in enhancing the realism of the footstep sounds presented by using the non-interactive feedback system described in section 3. Participants sat on a chair passively receiving the audio-haptic simulations which were presented in the three conditions, alone (experiment 4), with soundscapes (experiment 5), and with the soundscapes plus the visual feedback (experiment 6). The experimental procedure was similar to the one utilized during the second part of the interactive feedback experiments. In particular the structure of the trials, the used surface materials, as well as the asked questions were the same. Participants were exposed to 12 trials, 6 simulating a walk and 6 simulating a run. The trials were presented once in randomized order.

All experiments were carried out in an acoustically isolated laboratory where the setups for the experiments were installed. Participants were asked to interact with a simple graphical user interface composed only by buttons to be pressed, and to collect their answers on a sheet.

A part of the experiment similar to the first part of the interactive experiments was not conducted because participants had to wear the shoes but they did not have to walk. Therefore it would have been obvious for them to look at the feet to find differences between the two parts of the trials. In addition the preference for the auditory or the audio-haptic feedback would have been deducted by the participants choices of the presented questions. Furthermore the experiments would have been too long, and participants could have answered randomly, because of the loss of attention. These aspects were assessed during a pilot test with 4 subjects in all three experiments.

Our hypotheses were that the majority of participants would have preferred the audio-haptic condition in both the trials A-AH and AH-A, and that the enhancement of the realism of the audio-haptic condition would have evaluated with higher ratings for experiments 2 and 3 compared to experiment 1.

5.1 Participants

Thirty-six participants were divided in 3 groups ($n = 12$) to perform the 3 between-subjects experiments. The 3 groups were composed respectively of 8 men and 4 women, aged between 19 and 27 (mean = 21.91, standard deviation = 2.42), 8 men and 4 women, aged between 19 and 26 (mean = 22.08, standard deviation = 2.06), and 7 men and 5 women, aged between 20 and 32 (mean = 23.75, standard deviation = 3.22).

All participants reported normal hearing conditions, normal or corrected-to-normal vision, and no locomotion problems. The sandals were the same adopted for the interactive experiments, therefore also in this case subjects wore shoes sizes from 41 to 45 (EUR).

5.2 Results

Tables 3 and 4 show the results of the three non-interactive experiments. The first noticeable thing emerging from results is that for the most part participants evaluated the haptic feedback as enhancing the realism of the simulations in all the experiments and in all the trials. The binomial test revealed a significant preference for the increment of realism in presence of haptic feedback ($p < 0.0001$ for all experiments) and for the decrement of realism in its absence ($p < 0.0001$ for all experiments). As regards the evaluations of the increase of realism in presence of haptic feedback, as well as the evaluations of the decrease of realism in its absence, results show that they are most of the times higher than 4.5, (i.e. towards the "very much"). From the comparison of the evaluations between the stimuli it is possible to notice that the surface materials can be ordered by the enhanced realism. Indeed in all experiments snow presents the highest ratings, and sand presents ratings higher than forest floor.

In addition, from a comparison between the three experiments both in the case of the walk and run,

TABLE 1
Results of the first part of the interactive feedback experiments.

	Experiment 1			Experiment 2			Experiment 3		
	% Difference	% Preference		% Difference	% Preference		% Difference	% Preference	
Trials	**Correct Answers**	**A**	**AH**	**Correct Answers**	**A**	**AH**	**Correct Answers**	**A**	**AH**
A-AH Snow	75	44.45	55.55	75	22.23	77.77	75	0	100
A-AH Sand	75	55.56	44.44	66.66	25	75	75	33.34	66.66
A-AH Forest floor	83.33	50	50	66.66	12.5	87.5	66.66	25	75
AH-A Snow	75	33.34	66.66	91.66	45.46	54.54	58.33	14.29	85.71
AH-A Sand	83.33	30	70	58.33	28.58	71.42	58.33	0	100
AH-A Forest floor	75	33.34	66.66	75	33.34	66.66	66.66	37.5	62.5
A-A Forest floor	75	-	-	75	-	-	91.67	-	-
AH-AH Forest floor	75	-	-	83.34	-	-	83.34	-	-

TABLE 2
Results of the second part of the interactive feedback experiments. For each stimulus the percentage of the chosen answers and the corresponding evaluation (mean and standard deviation) are shown.

	Trials A-AH	Presence of the haptic feedback			Trials AH-A	Absence of the haptic feedback		
		Increased	**Decreased**	**No difference**		**Increased**	**Decreased**	**No difference**
Exp. 1	**Snow**	100% 6.16±2.12	0%	0%	**Snow**	16.67% 5±1.41	75% 5.88±1.76	8.33%
	Sand	83.34% 4.9±2.13	8.33% 6±0	8.33%	**Sand**	0%	83.33% 4.7±1.94	16.66%
	Forest floor	75% 3.44±2	8.33% 4±0	16.67%	**Forest floor**	8.33% 4±0	66.67% 3.12±1.45	25%
Exp. 2	**Snow**	75% 5.77±2.33	25% 4±1	0%	**Snow**	25% 4.33±2.51	66.67% 6.12±2.1	8.33%
	Sand	75% 5±2.06	16.67% 2.5±2.12	8.33%	**Sand**	16.66% 3.5±3.53	83.34% 5.1±1.72	0%
	Forest floor	66.66% 4.87±2.69	16.67% 2±1.14	16.67%	**Forest floor**	16.67% 6±1.41	66.66% 2.87±1.95	16.67%
Exp. 3	**Snow**	91.67% 6.9±1.81	0%	8.33%	**Snow**	0%	91.67% 6.54±2.11	8.33%
	Sand	83.34% 6.2±2.25	8.33% 6±0	8.33%	**Sand**	0%	91.67% 6.36±1.91	8.33%
	Forest floor	83.34% 5.9±2.13	0%	16.66%	**Forest floor**	0%	83.34% 5.3±2	16.66%

it emerges that the average values of the increment of realism in trials A-AH, as well as of the decrement of realism in trials AH-A, are lower when the footsteps are simulated alone compared to when they are provided with soundscapes and with soundscapes plus visual feedback. In particular the highest ratings are present for experiment 6. However, the results of an ANOVA with repeated measures revealed that all such differences are not statistically significant.

6 Discussion

From a comparison of results from the first parts of the three interactive feedback experiments, it is possible to notice that on average participants did not notice the presence of the haptic feedback with significant higher percentages in experiment 1 compared to the other two. A deeper analysis conducted at subject level revealed that subjects could be divided in three categories: those who understood the difference in all trials, those who understood it some times, and those who never understood it. In particular the latter group was composed by 2 participants in experiment 1 and 2, and 3 participants in experiment 3. When at the end of the experiment they were told that the difference consisted in the haptic feedback, they reported that they were so totally driven by the auditory feedback in experiment 1 and 2 and by the visual feedback in experiment 3 that they even did not perceive the

TABLE 3
Results of the non-interactive feedback experiments (walking trials).

	Trials A-AH	Presence of the haptic feedback			Trials AH-A	Absence of the haptic feedback		
		Increased	Decreased	No difference		Increased	Decreased	No difference
Exp. 4	Snow	83.34% 5.1±3.24	16.66% 4±1.14	0%	Snow	16.67% 4±0	75% 5.55±2.87	8.33%
	Sand	75% 5±2.06	25% 5.33±3.78	0%	Sand	0%	91.67% 4.45±1.43	8.33%
	Forest floor	83.34% 3.6±2.06	16.66% 1.5±0.7	0%	Forest floor	8.33% 4±0	83.34% 4±2.58	8.33%
Exp. 5	Snow	83.34% 6.9±1.85	8.33% 5±0	8.33%	Snow	0%	83.34% 6.8±6.61	16.66%
	Sand	66.66% 5±2.26	16.67% 4.5±2.12	16.67%	Sand	0%	91.67% 5.27±2.24	8.33%
	Forest floor	91.67% 4.18±2.35	8.33% 7±0	0%	Forest floor	8.33% 8±0	83.34% 4.6±2.31	8.33%
Exp. 6	Snow	91.67% 5.18±2.27	0%	8.33%	Snow	16.66% 4±2.82	83.34% 6.1±0.99	0%
	Sand	91.67% 4.72±1.42	0%	8.33%	Sand	8.33% 2±0	91.67% 4.9±1.7	0%
	Forest floor	91.67% 4.09±1.51	0%	8.33%	Forest floor	8.33% 2±0	83.34% 3.9±1.44	8.33%

TABLE 4
Results of the non-interactive feedback experiments (running trials).

	Trials A-AH	Presence of the haptic feedback			Trials AH-A	Absence of the haptic feedback		
		Increased	Decreased	No difference		Increased	Decreased	No difference
Exp. 4	Snow	66.67% 4.5±3.29	33.33% 3.5±2.38	0%	Snow	16.66% 4.5±3.53	83.34% 5.1±2.18	0%
	Sand	100% 4.25±1.76	0%	0%	Sand	8.33% 5±0	91.67% 4.81±2.04	0%
	Forest floor	58.34% 4.14±1.67	33.33% 2.25±0.95	8.33%	Forest floor	8.33% 3±0	91.67% 3.9±2.58	0%
Exp. 5	Snow	83.34% 6.2±2.29	8.33% 5±0	8.33%	Snow	8.33% 3±0	91.67% 6.18±1.66	0%
	Sand	75% 5.77±1.92	25% 3±1	0%	Sand	8.33% 2±0	83.34% 5.9±1.52	8.33%
	Forest floor	83.34% 4.7±2.11	16.66% 4±2.82	0%	Forest floor	0%	83.34% 5.4±2.06	16.66%
Exp. 6	Snow	83.34% 5.6±2.79	8.33% 2±0	8.33%	Snow	0%	100% 5.33±1.82	0%
	Sand	91.67% 4.27±2.45	8.33% 4±0	0%	Sand	0%	100% 5±1.65	0%
	Forest floor	91.67% 4.45±2.42	0%	8.33%	Forest floor	0%	83.34% 4.5±1.71	16.66%

presence of the haptic feedback. In addition when in the second part of the experiment they were asked to focus on the vibrations provided by the shoes in order to evaluate the enhancement of the realism produced by the haptic feedback, either their ratings were among the lowest, or they reported that the presence of the haptic feedback did not produce any difference in the realism of the simulation compared to its absence. Clearly, from this result it is possible to conclude that the perception of the interactive haptic feedback provided at feet level by using the proposed system, varies in great measure from person to person.

Results of the second parts of the interactive feedback experiments as well as of the non-interactive feedback experiments confirmed our hypothesis that

the audio-haptic condition would have been preferred to the auditory one. Indeed at both interactive and non-interactive level, on average more than 66% of participants reported that the presence of the haptic feedback increased the realism of the simulation compared to when it was not provided, and its absence decreased the realism of the simulation compared to when it was present.
Nevertheless, in both the interactive and non-interactive feedback experiments some participants did not like the presence of the provided haptic feedback. The reasons of this lie in the fact that on one hand participants felt more comfortable without the proposed vibrations, and on the other hand the provided simulations did not match with their expectations.
However, most of the participants were satisfied by the proposed simulations, and this emerged also from the open comment they left at the end of the experience. In particular 9 participants in the interactive experiments and 11 in the non-interactive ones reported that the simulation of snow was the most convincing one. This aspect can be also noticed looking at the results illustrated in Tables 2, 3 and 4. In addition, it is possible to order the surface materials in terms of realism enhanced by the haptic feedback, with snow having the highest evaluations, and sand presenting evaluations higher than forest floor.

From a comparison between Tables 3 and 4, it is possible to notice that there are no substantial differences between the evaluations expressed by participants on the simulated walk and those on the simulated run.

As regards the effect of the context on the perceived realism induced by the haptic feedback, our hypotesis was confirmed. Indeed results of the second part of the interactive feedback experiments, as well as of the non interactive feedback experiments, show that the average ratings for the experiments in which the audio-haptic simulations were provided alone were lower than those in presence of soundscapes or soundscapes plus visual feedback, although not in a significant way. However, the experimental design followed a between-subjects approach, and a confirmation of this result necessitates further investigations.

Overall our results provide evidence of the importance of the use of the tactile channel to enhance the walking experience in both multimodal interactive and non-interactive contexts. This result is in accord with the findings reported in [11] and [15] which showed that plantar vibrotactile feedback plays a relevant role in the perception of both real and simulated ground surfaces during the act of walking.
However, the fact that not all participants preferred the proposed interactive and non-interactive haptic feedback might be due to the quality of the surfaces simulations. This consideration is supported by the fact that the results reported in our previous works [18], [17] on audio-haptic discrimination tasks of simulated ground surfaces revealed that audition played a role of dominance on the haptic modality, while audio-haptic recognition tasks involving real materials suggested that the haptic modality is the dominant one [11]. Nevertheless, the different evaluations expressed by each participant may be linked to the individual propensity to be involved in the simulations [28].

7 Conclusion

In this paper we proposed several experiments to investigate the role of haptic feedback in enhancing the realism of a walking experience in multimodal environments both in an interactive and a non-interactive configuration. Results of the experiments show that haptic feedback delivered at feet level significantly enhances the perceived realism. However, the subjects' reaction was divided among those who appreciated the haptic feedback, and those who found it annoying. Nevertheless this might be due on one hand to the limits of the haptic simulation and on the other hand to the different individual propensity to be involved in the simulations.

Considering the overall simulated architecture, several subjects found it satisfactory. This is especially the case for the environment simulating snow, where high ratings were reported in all experiments.

The results here reported provide evidence that the use of the haptic channel can lead to more realistic experiences in both interactive and non-interactive configurations. Indeed our findings can find application in the context of physical navigation in multimodal virtual environments as well as in entertainment systems, for example to enhance the user experience of watching a movie or playing a video game.

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